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SINGLE OBJECTIVE LENS FOR USE
WITH CD OR DVD OPTICAL DISKS

Background and Brief Summary of the Invention

The present invention relates to a single objective lens that can be used with either CD optical disks or DVD optical disks.

Several different formats of optical disk are known in the prior art. The two most commonly used formats are the CD and the DVD. These two optical disk formats store different data densities; the DVD uses a much smaller track and much smaller "pits" to record a higher data density. The CD (Compact Disk) appears in wide use as both a CD-DA (Company Disk-Digital Audio) and a CD-ROM (Compact Disk-Read Only Memory); the format is identical for these two species. The DVD (Digital Versatile Disk) appears in use as a digital video (movie) storage or an extended computer memory product.

Data records on both CD and DVD formats are in "pits" formed in a reflective surface of the disk. These "pits" are actually in the form of short "trenches" that lie along a track that spirals around the disk surface. The CD "pit" is typically 0.50 micrometer (μM) wide and between 0.83 to 3.05 μM long. The track pitch is 1.6 μM and the depth of the "pit" is 0.20 μM . To achieve higher data density, the DVD "pit" is typically 0.3 μM wide and between 0.40 to 1.5 μM long. The track pitch is 0.74 μM and the "pit" depth is 0.16 μM . The CD can reliably record about 650MB of digital data whereas the DVD can reliably record about

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1 4.7GB of digital data on one side of the disk (both sides can be
2 used on a DVD).
3

4 The width and depth of the CD "pit" was determined by
5 early optical fabrication technology which limited the objective
6 lens to 0.45 NA (Numerical Aperture), and by early laser diode
7 technology (a 780 nm emission line). Because cost-effective
8 objective lenses could be made no faster than 0.45 NA (i.e. a
9 relative aperture of f/1.11) and lower wavelength laser diode
10 emission lines were not available, the size of a diffraction-
11 limited laser spot image was limited to 1.0 μm at the Full-Width-
12 Half-Maximum intensity points (FWHM). The CD "pit" depth is
13 chosen to be one-fourth of the laser wavelength (0.20 μm) and the
14 "pit" width is chosen to be about half the laser spot diameter
15 (0.50 μm). This arrangement permits about half of the wavefront
16 in the laser spot to reflect from the bottom of the "pit" and
17 about half of the wavefront to reflect from the surface surround-
18 ing the "pit." The two reflected components are half a wave-
19 length out of phase so they interfere destructively. No signal
20 is returned to the objective lens when a "pit" is present. When
21 no "pit" is present, the full wavefront reflects from the
22 surrounding surface and light is returned to the objective lens.
23 This is the digital encoding process for most optical disks.
24 There are other subtle effects that this encoding process
25 introduces such as diffraction at the edges of the pit, but the
26 interference process is thought to be the principal phenomenon.

1 The newer DVD format has been enabled by two technology
2 developments; a 650 nm laser diode has become commercially viable
3 and 0.60 NA objective lenses have become cost-effective. The
4 combination of these two factors produces a diffraction-limited
5 laser spot with 0.64 μm FWHM, so the DVD "pit" width becomes 0.32
6 μm and the "pit" depth becomes 0.16 μm .

7 Several optical disk products have been produced in the
8 prior art that combine CD and DVD formats in the same optical
9 reader. In order to achieve this goal, the prior art uses two
10 laser diodes plus two lenses and moves either one set (laser
11 diode plus objective for CD format) or the other set (laser diode
12 plus objective for DVD format) over the disk that is to be read.
13 No prior art single objective design is known that can operate
14 with either the CD or DVD formats.

15 The invention of this application is a single lens that
16 can operate with either the CD format (with 780 nm laser diode)
17 or with the DVD format (with 650 nm laser diode). No moving
18 parts are required with this invention because the appropriate
19 laser diode can be turned on electrically and introduced to the
20 objective lens via a dichroic beamsplitter or a grating struc-
21 ture.

22 Brief Description of the Drawings

23 Fig. 1 is a schematic representation of a typical prior
24 art CD objective lens;

25 Fig. 2 shows the wavefront error of the prior art objec-
26 tive lens shown in Fig. 1;

1 Fig. 3 is a graphical representation of the depth of focus
2 defined as the RMS wavefront error of the prior art lens of Fig.
3 1;

4 Fig. 4 shows a single objective lens according to the
5 present invention and related system components operating with
6 either a CD format (.45 NA ray fan and thick disk substrate) or a
7 DVD format (.60 NA ray fan and thin disk substrate);

8 Fig. 5 shows a schematic representation of one embodiment
9 of the single objective lens according to the present invention
10 using aspheric surfaces;

11 Fig. 6 is a graphical representation of the wavefront
12 errors of the single objective lens shown in Fig. 5;

13 Fig. 7 is a graphical representation showing the depth of
14 focus defined as the RMS wavefront error for the single objective
15 lens shown in Fig. 5;

16 Fig. 8 is a schematic representation of a second and
17 preferred embodiment of the present invention using one diffrac-
18 tive and one aspheric surface;

19 Fig. 9 is a graphical representation showing the wavefront
20 errors for the lens design shown in Fig. 8;

21 Fig. 10 is a graphical representation showing the depth of
22 focus properties of the system shown in Fig. 8;

23 Fig. 11 is a graphical representation of the percentage of
24 light focused by a diffractive surface showing wavelength
25 dependency; and

1
2 Fig. 12 is an exaggerated representation of the diffrac-
3 tive surface used in the preferred embodiment shown in Fig. 8.
4

Detailed Description of the Drawings

5 Fig. 1 shows a typical prior art CD objective operating at
6 0.45 NA and with a 780 nm laser diode source. This objective
7 uses injection molded PMMA plastic plus aspheric surfaces on both
8 sides of the lens. The objective forms a diffraction-limited
9 image on the rear surface of a 1.2 mm thick polycarbonate plastic
10 cover on the CD.

11 Fig. 2 shows the wavefront error of the prior art system
12 of Fig. 1 (the horizontal axis is the dimension across the lens
13 aperture and the vertical axis is the wavefront error). The
14 Marechal condition for a diffraction-limited optical system is
15 0.070 RMS waves. This prior art lens has a 0.035 RMS wavefront
16 error and is diffraction-limited by this criterion. This RMS
17 wavefront error is equivalent to a 0.140 P-V wavefront error and
18 the Rayleigh criterion for a diffraction-limited lens is a
19 wavefront error of less than 0.250 PV waves, so the lens is
20 diffraction-limited by this criterion as well.

21 Fig. 3 shows the RMS wavefront error of the prior art
22 system of Fig. 1 as a function of the depth of focus. Because
23 the objective must be rapidly auto-focused during reading
24 operations, there must be a useful depth of focus where the
25 objective performance is essentially diffraction-limited. This
26 prior art nominal design is essentially diffraction-limited over
a +/-1.5 micrometer range. When the objective is manufactured,

1 fabrication tolerances reduce performance and the useful depth of
2 focus is reduced to about +/-1.0 micrometer. The essentially
3 diffraction-limited depth of focus requirement forces very
4 stringent fabrication tolerances on this class of objective lens.
5

6 Fig. 4 shows the first embodiment of the objective lens
7 design of the present invention that could operate with both CD
8 and DVD formats. Lens 20 has a large aperture that permits ray
9 fans for either a 0.45 NA (and 780 nm laser diode) operation or a
10 0.60 NA (and 650 nm laser diode) operation. This figure shows
11 that the central zone of the lens must be used to control the
12 0.45 NA and 780 nm laser diode operation and that the outer zone
13 can be independently designed for the 0.60 NA and 650 nm laser
14 diode operation. However, the central zone will also contribute
15 to the 0.60 NA and 650 nm laser diode operation and this is the
16 reason that prior art objectives designers have not been able to
17 use a single element objective for both CD and DVD reader
18 systems. As shown in Fig. 4, disk 30 may either be a DVD format
19 disk or a CD format disk. Disk support and drive means shown
20 generally as 40 includes a conventional drive plate 41, spindle
21 42 and drive motor 43 as known in the art. First and second
22 laser diodes 51 and 52, respectively, operate with output beams
23 of approximately 780 nm and 650 nm, respectively. The laser
24 diode output beams pass through beam-splitters 71 and 72 and are
25 directed towards collimating lens 60. Light 61 exiting the
26 collimating lens 60 passes through single element objective lens
20, is reflected from the CD or DVD disk, and is deflected by

beam-splitter 72 onto photodetector 80, where changes in output power are utilized to read the disk, as is known in the art. It is significant that the single element objective lens 20 of the present invention is positioned between the beam-splitter 70 and disk 30 in a pathway of collimated light. Several of the prior art systems position the objective lens in a pathway of non-collimated light requiring that the placement of the objective lens be very precise. The placement of components shown in Fig. 4 can be varied without departing from the invention and alternate beam-splitters and collimators may be used. Although the embodiments shown and discussed herein disclose lasers 51 and 52 operating at 780 nm and 650 mn, it is to be understood that the invention can be applied to the general case wherein lasers can be operated with different output wavelengths including shorter wavelength lasers as they become commercially available. Another significant aspect of the single element objective lens 20 as used in the present invention is that the lens is a single optical element in contrast to the typical two element prior art design which utilizes either an objective lens and hologram or an objective lens and a second lens element. Full alignment of both elements in the prior art requires alignment of five degrees of freedom of the two combined elements (centration of both elements and two degrees of tilt for each element), whereas the use of the single element, fixed objective lens 20 of the present invention greatly simplifies alignment of the lens.

1 The first embodiment of the present invention is shown in
2 greater detail in Fig. 5. This is a molded COC (Cyclic Olefin
3 Copolymer) plastic lens 20 with aspheric first surface 21 and
4 aspheric second surface 22. This invention uses the fact that
5 the polycarbonate disk cover plate 30 varies from 0.6 mm in the
6 DVD format 31 to 1.2 mm in the CD format 32 and that the spheri-
7 cal aberration introduced by the plate is twice as large for the
8 CD format. Concurrently, the objective DVD format NA is 0.60 and
9 introduces nearly 2.4 times the spherical aberration that the CD
10 format 0.45 NA introduces to the system. The spherical aberra-
11 tion of the cover plate and the spherical aberration of the
12 objective, therefore, work in concert for the CD and for the DVD
13 systems to produce similar amounts of system spherical aberra-
14 tion. Although the amount of spherical aberration for the two
15 systems is similar, the distribution of spherical aberration
16 across the aperture of the lens is different for the two systems
17 and this limits the aberration correction to a less than diffrac-
18 tion-limited condition. In addition, the CD and DVD systems
19 operate at different wavelengths and the refractive index of the
20 plastic changes with wavelength in such a way that the distribu-
21 tion of spherical aberration across the lens aperture also
22 changes with wavelength. Optical designers recognize this
23 condition as spherochromatism.

24 The first embodiment of this invention utilizes the
25 discovery that a single element objective lens can be used for
26 both CD and DVD operation because the amount of spherical

aberration for the two systems is similar and can be controlled to nearly diffraction-limited levels by the correct choice of aspheric surface profiles in the central zone 25 and in the outer zone 26 of the objective.

Fig. 5 shows the first embodiment objective. The 0.45 NA, 780 nm ray fans are shown passing through the central zone 25 of the lens aperture. The 0.60 NA, 650 nm ray fans are shown extending across the full aperture of the lens, which includes the central zone 25 and outer zone 26. Although the diameter of the outer zone appears only slightly larger than the central zone diameter, nearly 0.5 of the energy in the DVD system resides in this outer zone. The ability to independently modify these outer zone surface profiles gives the designer a strong control of the DVD system aberrations that is independent of the CD system aberrations. The two different cover plate thicknesses are shown in this figure. The laser diodes and disk drive are not shown.

The first surface 21 and second surface 22 shown in Fig. 5 can be described in the following mathematical terms:

a first aspheric surface defined as:

$$sag_1 = \frac{\rho_1 r^2}{1 + SQT[1 - (1 + k_1)\rho_1^2 r^2]} + A_1 r^4 + B_1 r^6 + C_1 r^8 + D_1 r^{10} \dots$$

and a second surface having an aspheric profile defined as:

$$sag_2 = \frac{\rho_2 r^2}{1 + SQT[1 - (1 + k_2) \rho_2^2 r^2]} + A_2 r^4 + B_2 r^6 + C_2 r^8 + D_2 r^{10} \dots$$

1 Where sag represents sagittal height, and
2

3 ρ_1 = 1/radius of first surface vertex
4 ρ_2 = 1/radius of second surface vertex
5 k_1 = conic coefficient of first surface ($-3.5 < k_1 < 0.0$)
6 k_2 = conic coefficient of second surface ($-15.0 < k_2 < -5.0$)

7 A_1 through D_1 = general aspheric terms and are non-zero on at
8 and least one of said first or second surfaces, and
9 A_2 through D_2

10 the vertex curvatures ρ_1 and ρ_2 satisfy $0.667 < \frac{|\rho_1|}{|\rho_2|} < 1.50$

11 Fig. 6 shows the wavefront errors of the first embodiment
12 objective (shown in Fig. 5) for both the CD and DVD operating
13 conditions. Note that the P-V wavefront error for the DVD case
14 is about the Rayleigh limit of 0.250 wave.

15 Fig. 7 shows the RMS wavefront error for the system of
16 Fig. 5 through the depth of focus and verifies that the nominal
17 system is at the limit of being diffraction-limited and that
18 there is essentially no margin for fabrication tolerances. The
19 first embodiment is a theoretically viable solution but it
20 requires very tight manufacturing processes to produce economic
21 yields.

22 The preferred embodiment uses a diffractive surface on one
23 side of the objective. Diffractive surfaces introduce an addi-
24 tional aberration-correction feature that refractive aspheric
25 surfaces cannot provide. Diffractive surfaces change the
26 wavefront differently for different wavelengths. A positive
powered diffractive surface bends longer wavelength light more

1 than shorter wavelength light. This is the opposite behavior of
2 a refractive aspheric surface. This new aberration-correction
3 feature permits a single element objective lens to correct most
4 of the spherochromatism that limits the performance of a simple
5 refractive aspheric lens.

6 Fig. 8 shows the preferred embodiment single element
7 objective lens 120. The first surface 121 nearest the disk is
8 aspheric and the second surface 122 furthest from the disk has a
9 diffractive surface imposed on a spherical base curve. The
10 diffractive surface provides the same aspheric correction of
11 spherical aberration provided by a refractive aspheric surface
12 but also provides spherochromatism correction. The objective has
13 a slightly different back focal distance for the two wavelengths
14 of interest but this is unimportant because the autofocus
15 mechanism brings the objective to its best focus.

16 Diffractive surfaces are known in the prior art where they
17 are widely used to correct the chromatic aberration of a singlet
18 operating over a broad spectral band or to correct the spherical
19 aberration of a singlet over a very narrow spectral band. The
20 use of a diffractive surface to correct spherochromatism of a
21 singlet operating at two different wavelengths is not known in
22 the prior art.

23 A diffractive surface consists of microscopic grooves in
24 the surface of an optical element. The grooves are widest at the
25 center of the optical element and progressively decrease groove
26 width toward the periphery of the element. The groove width is

similar in magnitude to the wavelength of light being used, so the grooves act as a diffraction grating to bend the light. The bending of light is due to diffraction rather than refraction (as produced by Fresnel lenses). Because the groove widths become smaller near the element periphery, the incident wavefront bends more near the edge of the optical element than at the center and the wavefront is therefore focused by diffraction.

Because diffraction is wavelength dependent, the wavefront focusing changes with wavelength to correct chromatic aberration. Because the rate at which the groove widths change can be adjusted to make the surface behave like an aspheric refractive surface, spherical aberration can be corrected.

Fig. 12 shows an exaggerated view of the diffractive surface. The actual groove depth is about 1.0 micrometer. The diffractive surface is described by a polynomial phase function which expresses how many waves of optical path are added or subtracted from each radial zone of the wavefront. The polynomial phase function is

$$\text{Phase} = C_2 r^2 + C_4 r^4$$

Where C_2 = diffractive power term
which controls chromatic
aberration correction

and $0.01 < C_2 < 0.05$

C_4 = aspheric power term
which controls spherical
aberration correction

and $0.0005 < C_4 < 0.005$

1
2 The first surface 121 shown in Fig. 8 can be described
3 mathematically as follows:
4

5 a first aspheric surface defined as:
6

T | 40 X
7
$$sag_1 = \frac{\rho_1 r^2}{1 + SQT[1 - (1 + k_1)\rho_1^2 r^2]} + A_1 r^4 + B_1 r^6 + C_1 r^8 + D_1 r^{10} \dots$$

8 the second surface 122 has a spherical profile on which is
9 imposed a diffractive surface 122d. The diffractive surface 122d
10 has a polynomial phase function with at least the second and
11 fourth power terms non-zero where
12

13 Phase = $C_2 r^2 + C_4 r^4$
14

15 Fig. 9 shows the wavefront error for the diffractive
16 objective of Fig. 8. It is significant that the wavefront error
17 vertical scale is ten times more sensitive than the prior plots.
18 The wavefront error is essentially zero and the more sensitive
19 scale is needed to see any wavefront error in this plot.
20

21 Fig. 10 shows the depth of focus properties of the
22 diffractive objective of Fig. 8. The performance of the 0.45 NA,
23 780 nm system is better than the prior art. This permits a
24 slightly greater fabrication tolerance margin compared to prior
25 art objective lenses. The 0.60 NA, 650 nm nominal system depth
26 of focus is about ± 1.0 micrometer. After fabrication tolerances
 are considered, the depth of focus will be on the order of ± 0.7
 micrometer. This is equivalent to the depth of focus that can be
 achieved by a 0.60 NA, 650 nm objective that only operates with a
 DVD format reader.

1 Fig. 11 shows an important feature of diffractive sur-
2 faces. The percentage of light that is focused by a diffractive
3 surface is wavelength dependent and several different images can
4 be produced in different diffraction orders. The proper choice
5 of the diffractive surface depth will cause essentially all of
6 the energy in one wavelength to be in the image of the preferred
7 first diffraction order. Because the optimum depth is wavelength
8 dependent and the laser diodes operate at 780 nm and 650 nm, not
9 all of the energy in these two wavelengths can be directed into
10 their respective first order images. The depth of the diffrac-
11 tive surface of this invention is, therefore, chosen midway
12 between these two wavelengths at a wavelength value of 715 nm.
13

14 Fig. 11 shows that 0.97 of the energy is directed to the
15 respective first order images when this condition is met. The
16 remaining 0.03 of the energy is primarily directed into the zero
17 diffraction order and is distributed over a large area of the
18 optical disk and produces a negligible background signal.

19 Modifications of design may be made without departing from
20 the invention. For example, the diffractive surface may be
21 carried by the lens surface 21 closest to the disk. Various
22 types of collimators and beam-splitters may be used as well as
23 laser diodes of various wavelengths. Various materials may be
24 used for the objective lens, including glass and PMMA.

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